

Implications of Confirmation of the LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Signal

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Neutrino oscillations have been observed in solar and atmospheric neutrinos, and in the LSND accelerator experiment. The Standard Model cannot accommodate all three positive results. The solar and atmospheric results have been confirmed. An oscillation signal seen by MiniBooNE will validate the oscillation signal seen by LSND. The question then becomes one of refining the Standard Model to allow for these three results. Four theories which can accommodate all three oscillation observations are the existence of sterile neutrinos, CP(T) violation, the existence of variable mass neutrinos, and small Lorentz violations. The Spallation Neutron Source (SNS), located at Oak Ridge Laboratories, Oak Ridge, Tennessee, will provide an ideal site to test these hypotheses. The SNS, due to turn on in 2008, will supply a high intensity neutrino source of known flux and energy spectrum. This source permits experiments to probe the high Δm^2 region for measurements, where a positive signal from MiniBooNE would lie.

1. Introduction

Neutrino oscillations have been observed at three different mass scales. Oscillations of solar neutrinos are seen as a deficit of ν_e from the sun. These oscillations were first observed by the Homestake [1], SuperKamiokande [2], SAGE [3], and GALLEX [4] experiments, and later confirmed by SNO [5] and KamLAND [6]. Solar oscillations occur at a Δm^2 of approximately $8 \times 10^{-5} \text{eV}^2$. Oscillations in atmospheric neutrinos ($\Delta m^2 \approx 2 \times 10^{-3} \text{eV}^2$) are seen as a deficit in the ratio of ν_μ to ν_e (Kamiokande [7]), and in a zenith angle discrepancy in the upward direction (SuperKamiokande). This result has been confirmed by K2K [8]. The third regime in which neutrino oscillations have been observed is at the mass scale of $\Delta m^2 \approx 0.1 \rightarrow 10 \text{eV}^2$. This result was observed by the LSND [9] experiment, and is currently awaiting confirmation.

In the Standard Model there are three active neutrinos. In this scenario a summation law holds such that $\Delta m_{12}^2 + \Delta m_{23}^2 = \Delta m_{13}^2$. The three mass scales of observed oscillations do not follow this law. Therefore, one of the results is faulty or there exists physics beyond the Standard Model.

The solar and atmospheric oscillations have been observed and confirmed by several experiments. Experiments such as KARMEN [10] and CHOOZ [11] have attempted to confirm the LSND result; so far these experiments have produced null results. However, none of these experiments have fully explored all of the LSND allowed regions. The MiniBooNE [12] experiment will make a definitive test of the LSND signal.

1.1. MiniBooNE

To confirm or refute the LSND result an experiment is needed which will cover all of the LSND allowed region in $\sin^2 2\theta$ - Δm^2 space, with a similar L/E and different sources of systematic uncertainties. This experiment is MiniBooNE. The MiniBooNE experiment is covered elsewhere in full detail and will only briefly be described here [12].

MiniBooNE is a fixed target experiment which directs an 8 GeV proton beam onto a beryllium target. Positive particles produced by this collision (primarily pions and kaons) are collimated by a magnetic focusing horn. These particles enter a 50 meter decay region where they decay in flight to produce a ν_μ beam. The neutrinos then travel through approximately 490 meters of a dirt absorber before entering the MiniBooNE detector.

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The energy of these neutrinos is ≈ 700 MeV, providing an L/E of ≈ 0.8 m/MeV (compared to the LSND L/E of ≈ 1 m/MeV). The MiniBooNE detector is a spherical tank filled with 800 tons of pure mineral oil. The inside of the tank is lined with PMTs, providing 10% photocathode coverage. Different beam energy, beam duty cycle, and oil allow MiniBooNE drastically different systematic errors than those found at LSND.

2. Physics of a Positive LSND Result

The Standard Model cannot accommodate a positive oscillation result from all three sectors (solar, atmospheric, LSND). Should MiniBooNE confirm the LSND result, the driving question in neutrino physics experiments will be determining the physics which would explain all three positive results. For brevity's sake only four theories will be touched on in this proceeding.

2.1. Sterile Neutrinos

The existence of additional neutrinos has been proposed. These “sterile” neutrinos are weak isospin singlets and do not engage in weak interactions. Sterile neutrino models are known as “3+n”, where 3 refers to the number of active neutrinos in the Standard Model and n is the number of sterile neutrinos. Models with one and two additional sterile neutrinos have been studied. Of the tested models, the 3+2 theory has the best fit to current oscillation data. In these theories the high mass eigenstates are composed almost entirely of the sterile neutrino flavor eigenstate, while the lower mass states are composed of the active eigenstates. [13] [14]

2.2. Mass Varying Neutrinos

All oscillation results may be accounted for if we permit the three active Standard Model neutrinos to have variable masses which depend on the value of a scalar field A . In this model sub-gravitational strength interactions between ordinary matter and A naturally occur. The value of A (and thus the mass of the neutrino) will change depending on the presence or lack of matter. [15] [16]

2.3. Lorentz Violations

A small Lorentz symmetry violation would explain all three positive oscillation results. Lorentz violations cause the oscillation to be dependent upon the direction of propagation, and thus would be easy to search for. The size of the violation required to accommodate oscillation data lies in the range expected for effects at the Planck scale in the presence of an underlying unified theory of general relativity with the Standard Model. [17]

2.4. CPT Violation

Finally, there could exist CP or CPT violation. In the CPT model there is no need to introduce additional sterile neutrinos. The oscillation results can be explained by allowing the Δm^2 of ν (and thus the probability of oscillation) to differ from that of the $\bar{\nu}$. This effect can be tested most cleanly by choosing an experiment which is capable of running in neutrino and anti-neutrino mode.

3. Tests of New Physics Theories

Several facilities may be used to test these new physics theories. This proceeding will focus on tests which may be done using the MiniBooNE detector, and using a MiniBooNE-like detector at the SNS.

3.1. MiniBooNE

The MiniBooNE detector is an excellent place to test these new physics theories. Mass varying neutrinos and Lorentz violations can be tested on the data used to perform the oscillation measurement. For example, a possible indication of mass varying neutrinos would occur if MiniBooNE observes a positive oscillation result in the mass range excluded by BUGEY [19] (~ 0.1 to 0.25 eV²). The oscillation signal can be plotted as a function of sidereal position. Any variations would indicate Lorentz violation.

Running MiniBooNE in anti-neutrino mode will provide a second data set which would be necessary to test for CP violations. The construction of a second MiniBooNE tank located further upstream from the current detector would allow two measurements of the neutral current (NC) cross

section. A difference in the NC rate between the two detectors would indicate an oscillation into a sterile neutrino.

While it is possible to test these new physics theories at MiniBooNE, using a neutrino beam formed from the decay-in-flight of mesons allows for very tricky systematic errors due to beam flux and cross sections. One way to avoid these systematics is to build a second detector at the MiniBooNE site. Another option is to move to a source which provides a decay-at-rest neutrino beam. Such a source is currently under completion at the SNS.

3.2. SNS

The SNS [20] is located at the Oakridge Laboratories, Oak Ridge, Tennessee, U.S.A. A one GeV proton beam, running with 700 ns pulses at a rate of 60 Hz, will impinge on a mercury target. The mercury will absorb the majority of the π^- and μ^- before decay; the primary neutrino flux comes from π^+ and μ^+ decay-at-rest. The lifetime of the π^+ and μ^+ relative to the beam window will provide good temporal separation of the ν_μ , ν_e , and $\bar{\nu}_\mu$. Primary backgrounds to experiments at the SNS will come from cosmic rays and machine neutrons.

Currently under consideration are two MiniBooNE-like detectors : one would be ~ 20 tons, located 20 meters from the neutrino source, and the other would be an 800 ton detector at a distance of 100 meters from the target and in the backward direction relative to the proton beam. These two detectors will be able to search for sterile neutrinos, test for CP/CPT and Lorentz violations, and test mass varying neutrino models. In addition, the smaller detector may be filled with a liquid or aqueous nuclei such as carbon or hydrogen. It could then be used to test cross sections which are vital for oscillation analyses at the SNS.

4. Conclusions

Should MiniBooNE confirm the LSND oscillation signal the next neutrino experiments will focus on determining which new physics model provides the mechanism for the oscillations, and

on measuring the oscillation parameters precisely. Four possible models have been described in this proceeding; however, there are many permutations and many other theories proposed to explain the three positive oscillation results. These new physics theories may be tested at several facilities, notably MiniBooNE and at the SNS.

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